

Coexistence Analysis for cross-duplexed air-to-ground system

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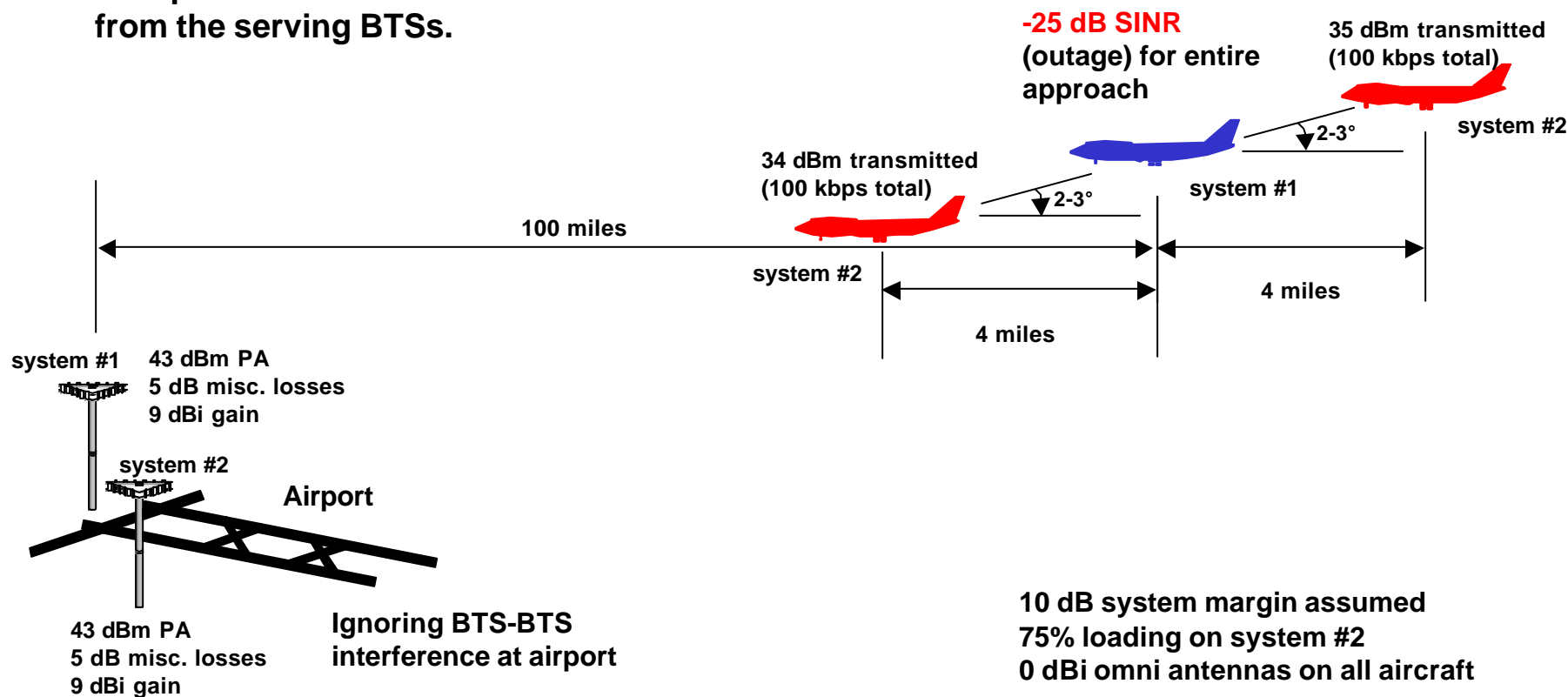
Introduction

- A beam selection diversity system on the aircraft is modeled in an attempt to try to combat the interference effects associated with cross-duplexed bands.
- System #1 (Airfone) and interfering system #2 (Aircell) are modeled after a generic 1xEvDO-type of system.
 - SINR is evaluated and related to throughput through a mapping that resembles 1xEvDO downlink rates.
- An example is presented that shows how this cross-duplexing scheme can result in a no-service condition for an entire airport approach or climb-out pattern.
- Monte Carlo simulations are performed with:
 - Realistic placement of base stations across the continental US.
 - *Non-uniform* density of aircraft based on airport traffic density.
 - Realistic sectored base station antenna patterns.
 - Power control modeled on the interfering aircraft.

Bottom Line: Even when using a switched-beam system on the aircraft, presence of the second, cross-duplexed system results in an unreliable service, especially near airports.

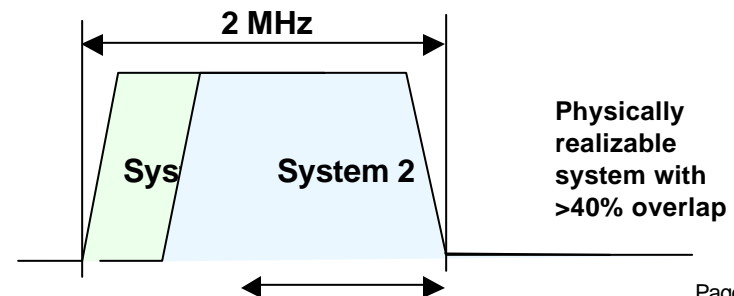
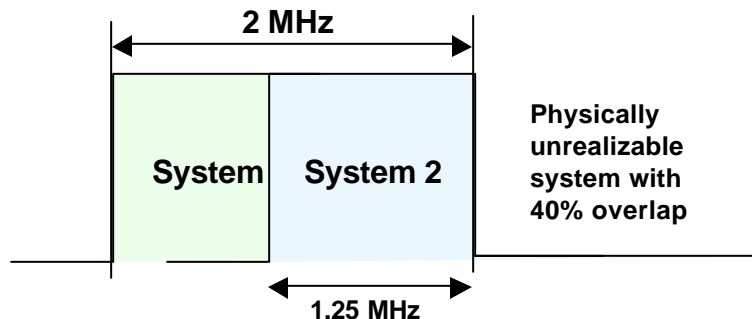
Airport approach example

- There are clearly cases where the cross-duplexed aircraft can cause serious harm.
- In the case below, the system #1 aircraft experiences an outage (using 1xEvDO) for the entire landing approach.
- This problem is exacerbated when the aircraft are further from the serving BTSs.



Simulation assumptions

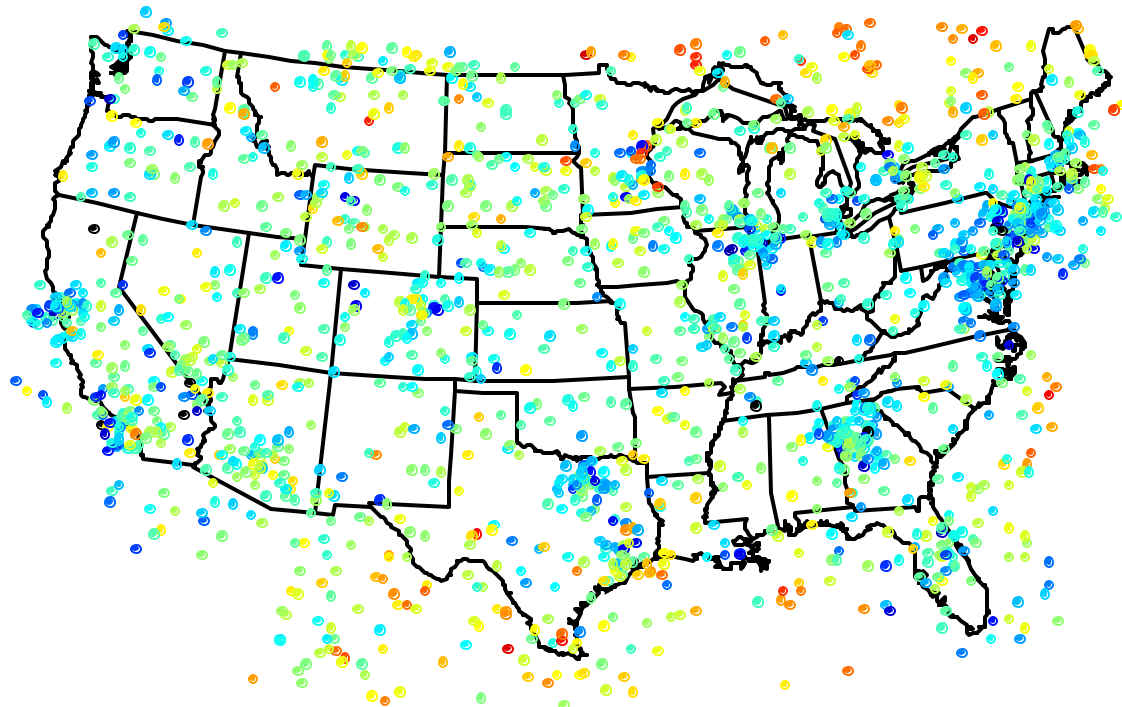
- A Monte-Carlo simulation was performed to determine if a 6 beam switched-antenna system on all system 1 aircraft would alleviate the interference problem.
- AirCell (system 2) proposes “band-swapping” so that the interference will occur from aircraft to aircraft and base station to base station.
 - In this simulation, we neglect the problems associated with base to base interference that may arise.
 - Aircraft to aircraft interference may be significant, since the radio horizon at 35,000 feet altitude exceeds 500 miles.
- Airfone (system 1) aircraft will receive transmission from
 - Serving base station.
 - Non-serving base stations (“same-system interference”).
 - Nearby (within radio horizon) system 2 aircraft.
 - Total received power from interfering aircraft is scaled back by a factor of 0.4 if spectrum of the two providers overlap by 40%.
 - 40% is an optimistic assumption, since the interfering systems will have some emissions outside of the 1.25 MHz allocated spectrum, i.e., it is not possible to realize a “brick-wall” filter that will allow a signal within the allocated 1.25 MHz, but none outside the 1.25 MHz.



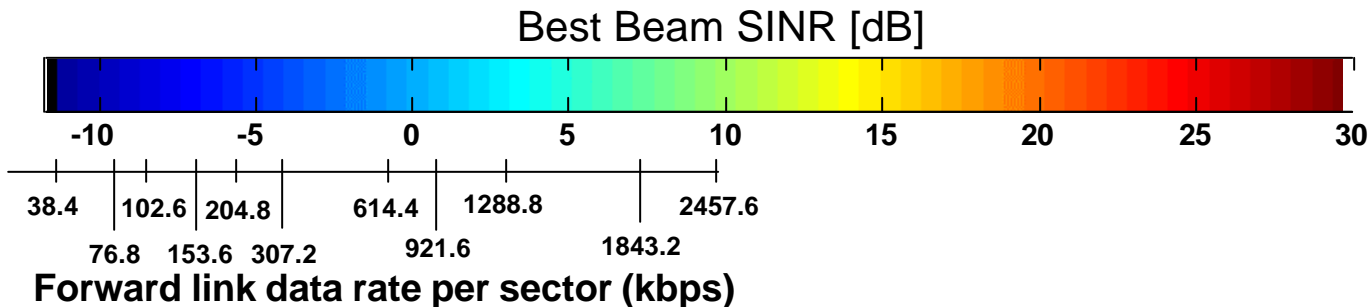
Single system performance

Max int pwr = -999 dBm, $N_{\text{inter}} = 125$, Overlap = 40%

Notice the non-uniform spatial distribution with clustering around major airports.



Performance on aircraft near the coast is worse than that of aircraft inland due to the restricted look-angle, i.e., they can only see base stations through 180° azimuth toward the coast.

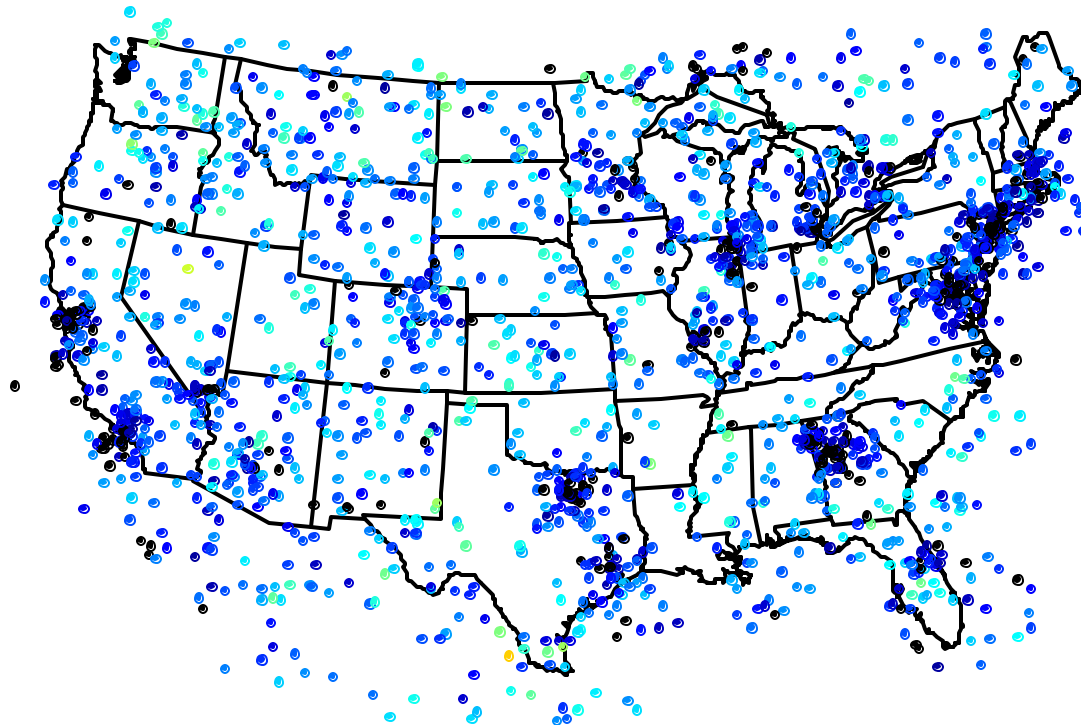


Performance Degradation with Two Systems

Max int pwr = 43 dBm, $N_{\text{inter}} = 2000$, Overlap = 40%

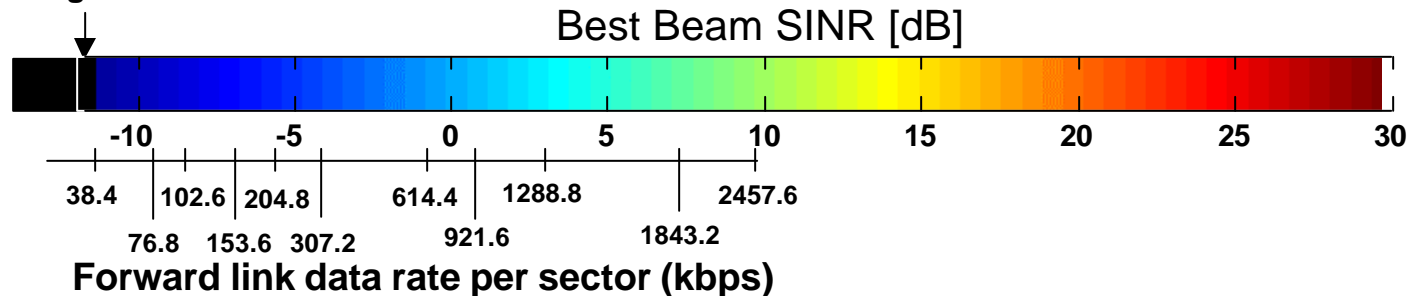
Performance of system #1 with system #2 present

- 50% market share for system #2 (2000 aircraft).
- 43 dBm maximum transmitted power from interfering aircraft (power controlled).



- Black dots denote coverage holes created by the interference.
- As expected, **coverage gaps** now exist near the major airports.
- Notice the generally lower SINR levels nationwide.

← outage



Conclusions

- There are serious limitations associated with the cross-duplex (band swapping) proposal.
 - Most notably, with just 2 interferers present in a take-off or landing situation, the aircraft can experience an outage for the entire climb-out or approach.
- A switched-beam antenna system simulation was performed in order to determine whether this interference mitigation technique could be used to allow two carriers with cross-duplexed bands (system 1 and system 2) to coexist within the same spectrum.
- One system is affected by the success of the largest provider, i.e., when one of the system gains market share, and hence has more aircraft in the air, the other system's performance is significantly degraded.
 - Forward link (ground-to-air) data rate drops significantly (from 1.7 Mbps to 400 kbps per sector).
 - Outage probability increases to an unacceptable level (from 0.2% to >12% nationwide, with large outage areas near major airports).
- All of these factors taken together indicate that such a cross-duplexed system results in an unpredictable and unreliable service under real-world conditions.

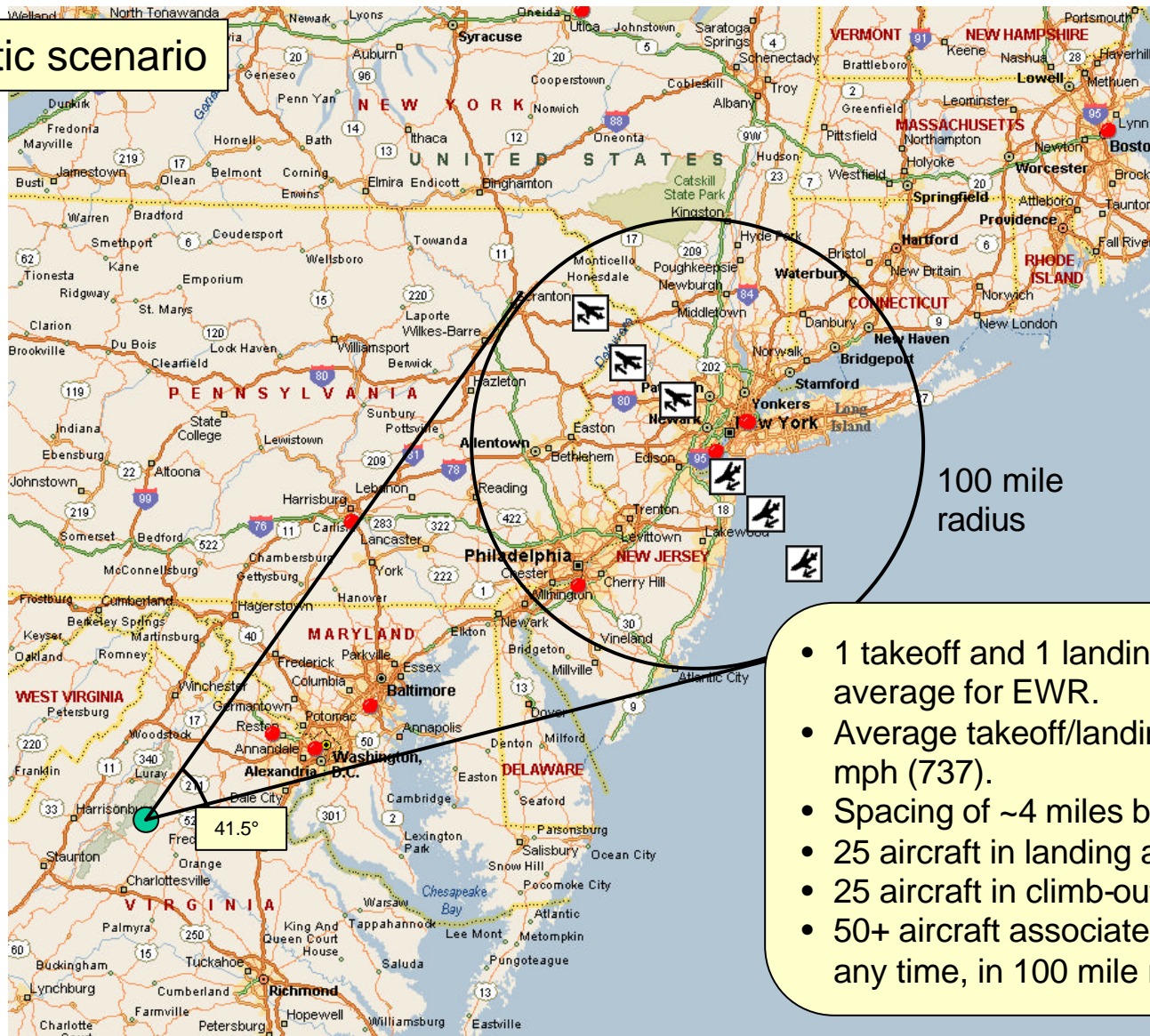
Additional technical information

Aircraft number and density estimate

- How many aircraft are in the air at any time of day (business hours)?
 - About 4,000 commercial aircraft, of which 60% are in the air at any time
 - About 8,000 private (corporate) aircraft, of which 20% are in the air at any time.
 - This results in about 4,000 aircraft in the air at any time.
 - With 150, 3 sector base stations, this results in ~9 aircraft max per sector for the addressable market.
- Next question is: what is the distribution of those aircraft?
 - To a first order approximation, we can create a disk around each airport and sprinkle users uniformly in radius and angle.
 - Data from EWR (Newark, NJ) suggest 1 aircraft per minute taking off and one aircraft per minute landing.
 - This leads to 50 aircraft associated with EWR in a 100 mile disk (assuming climb-out and approach speeds of a 737-400. 250 KIAS climb-out, 200 KIAS approach).
 - Data available (next slide) on passenger movements for top 20 international airports.
 - Can scale EWR estimate based on passenger movements to obtain number of aircraft associated with large airports and overlay this non-uniform distribution on top of a uniform distribution.

EWR as reference case

Realistic scenario



- 1 takeoff and 1 landing per minute on average for EWR.
- Average takeoff/landing speed 220 mph (737).
- Spacing of ~4 miles between aircraft.
- 25 aircraft in landing approach.
- 25 aircraft in climb-out.
- 50+ aircraft associated with EWR at any time, in 100 mile radius.

How to generate locations of interfering aircraft

Airport	Lat	Long	Aircraft within 100 Mile radius
ATLANTA (ATL)	33.64019	-84.432	124
CHICAGO (ORD)	41.97773	-87.908	110
LOS ANGELES (LAX)	33.93957	-118.405	101
DALLAS/FT WORTH (DFW)	32.89892	-97.0402	90
DENVER (DEN)	39.85638	-104.672	59
PHOENIX (PHX)	33.4352	-112.007	58
LAS VEGAS (LAS)	36.08237	-115.156	58
HOUSTON (IAH)	29.97949	-95.3325	57
SAN FRANCISCO (SFO)	37.61992	-122.378	57
MINNEAPOLIS/ST PAUL (MSP)	44.88269	-93.2187	56
DETROIT (DTW)	42.2163	-83.3484	53
MIAMI (MIA)	33.64019	-84.432	52
NEWARK (EWR)	40.69324	-74.173	50
NEW YORK (JFK)	40.64983	-73.7969	48
ORLANDO (MCO)	28.42997	-81.3154	46
TORONTO (YYZ)	43.68315	-79.6293	46
SEATTLE (SEA)	37.61992	-122.378	44
ST LOUIS (STL)	38.57377	-90.1588	44
Philadelphia (PHL)	39.87276	-75.246	43
Boston (BOS)	42.3675	-71.0103	42
BWI	39.17902	-76.6665	41
Reagan	38.84946	-77.0396	40
Dulles	38.94704	-77.4486	39
Laguardia (LGA)	40.77964	-73.8755	39
Hartford	41.73744	-72.65	38

- First sprinkle number of users specified to the left, uniformly in radius and angle around each airport in 100 mile disk. (total of 1,435)
- Next, sprinkle 4,000-1,435 aircraft uniformly over entire country.

- From previous slide, 50 simultaneous aircraft in air associated with EWR
- Other values scaled by passenger movements found at Airports Council International website: <http://www.airports.org>

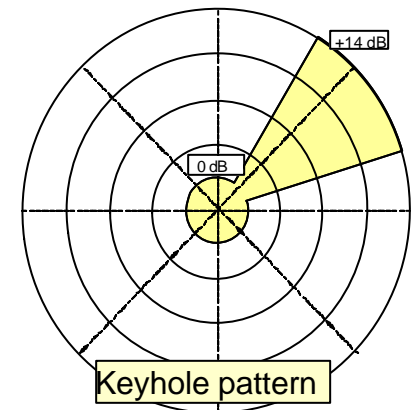
Aircraft Receiver and Physical Characteristics

- Desired Aircraft

- Aircraft randomly (non-uniform distribution as previously shown) located in latitude and longitude, but all are at 35,000 ft.
- Aircraft placed one at a time in 2000 different locations.
- Radio horizon is 278 miles with 100 foot antenna heights: $\sqrt{2}(\sqrt{h_1} + \sqrt{h_2})$ (h_1 and h_2 in feet)
- Aircraft has 6 beam switchable antenna system. Beam 1 points in direction of aircraft heading, beam 2 points 60° CW from beam 1, etc.
- “Keyhole” antenna pattern in azimuth is assumed for each beam.
 - Front-to-back ratio is 14 dB.
 - Boresight gain is 14 dBi.
 - Pattern is uniform in elevation.
- 5 dB cable and duplexer losses assumed at aircraft.

- Interfering Aircraft

- Aircraft randomly (non-uniform distribution as previously shown) located in latitude and longitude, but all are at 35,000 ft.
- Two cases simulated for transmit power from interfering aircraft
 - Max power of 33, 43 dBm.
- 75% system loading assumed.
- Omni (in azimuth) 0 dBi antennas on aircraft.

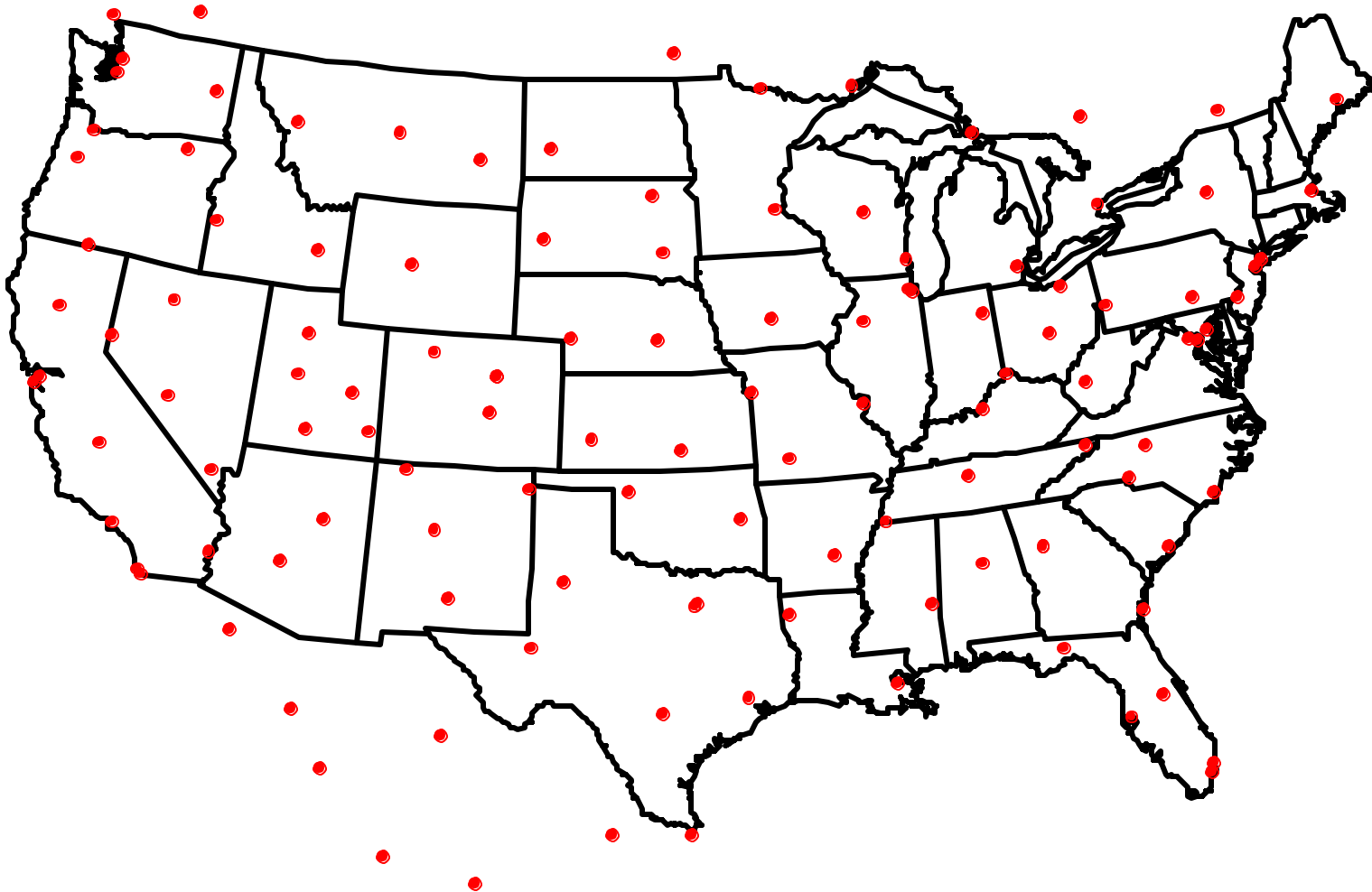


System 1 BTS Characteristics

- BTSs located near actual installed site locations.
- All BTSs transmit at constant 43 dBm power output from amplifier.
- Each BTS is configured as a 3 sector site.
- All BTS sectors oriented 0°, 120°, 240° from north.
- 3 sector antenna patterns used (both azimuth and elevation) from commercially available BTS antenna with 5 degree uptilt.
- 5 dB miscellaneous losses between ground transmitter and antenna.
- 10 dB of system margin was assumed for paths from each BTS to the aircraft, i.e., a uniform random variable (in dB) was chosen to account for misc. losses associated with antenna pointing errors, multipath fading, and other possible impairments.

System 1 Base Station Locations

- It is assumed that system 1 possesses 150 base stations generally located near airports.

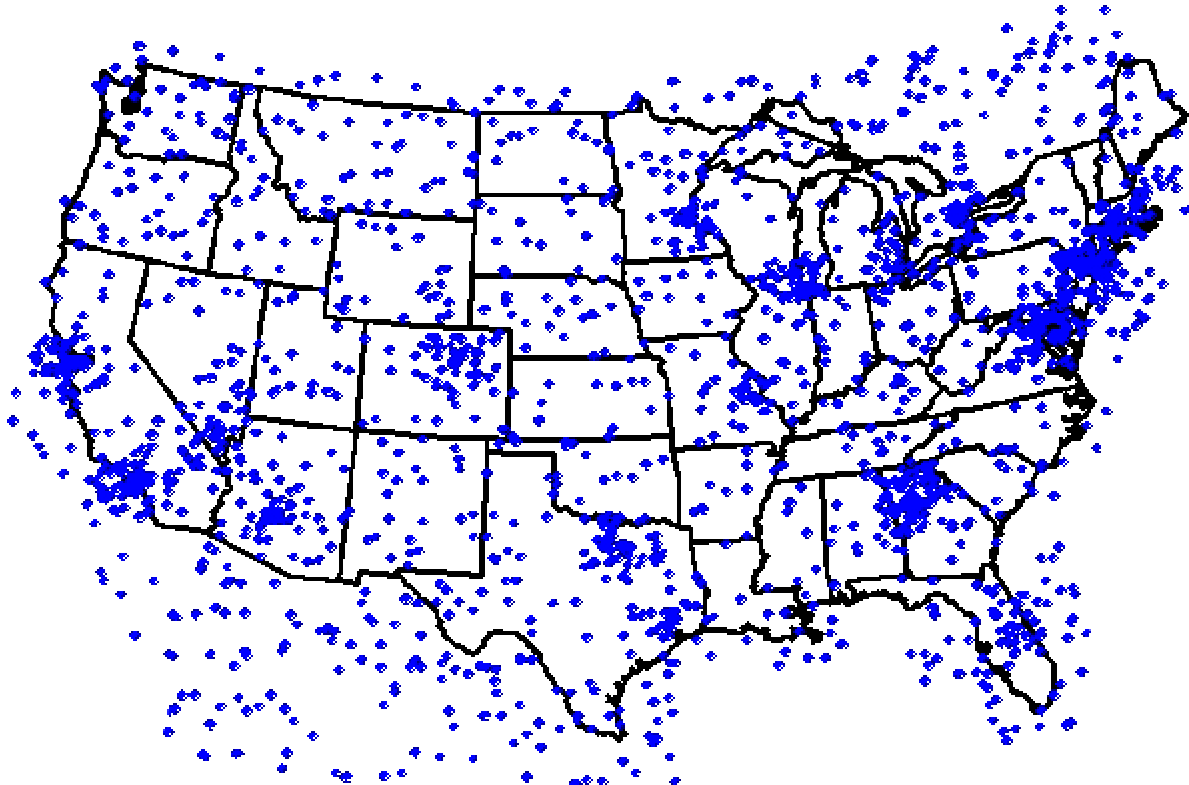


Monte Carlo Simulation Procedure

- Place specified number of interfering aircraft across continental US, randomly located according to previously discussed non-uniform distribution.
- Place a single “system 1” aircraft randomly from same distribution as used for interferers.
- For each of the 6 aircraft beams:
 - Calculate received signal strength with free space path loss to all base stations within the radio horizon.
 - Choose BTS with largest received signal strength as the serving BTS (desired signal).
 - Calculate received signal level from all other visible BTSs (interference).
 - Calculate receive signal level from all visible interfering aircraft (interference).
 - Calculate SINR.
 - Repeat for all beams.
- Record SINR for that location as that from the beam with the best SINR.
- Repeat...

Monte Carlo Points for Desired Aircraft

- Shown below is a representative distribution of points where the desired aircraft was placed for the Monte Carlo simulations. 2000 locations were used in the graphic below.
- If there are 4,000 aircraft in the air at any time, varying the number of interfering (system 2) aircraft represents various market penetration and market share rates.
- The distribution of interferers is based on this same distribution.



Interferer power distribution

For aircraft located uniformly in a disk around a serving BTS, the PDF of transmit power from each aircraft can be approximated as follows.

The probability that the aircraft's horizontal distance from the BTS is less than some chosen value y is

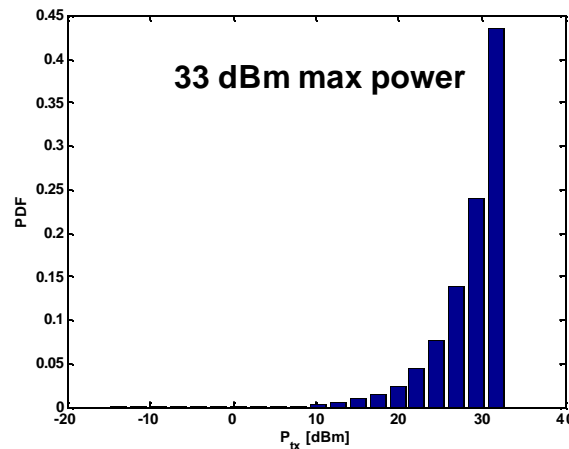
$$\Pr(d < y) = \frac{y^2}{D_{\max}^2}$$

Since we are assuming free space path loss to the BTS, in order to maintain constant power at the BTS, the aircraft must transmit with power proportional to d^2 and the CDF of the transmit power is now

$$\Pr(kd^2 < y) = \Pr\left(d < \sqrt{\frac{y}{k}}\right) = \frac{y}{kD_{\max}^2}$$

The factor k is chosen so that the aircraft can close the reverse link (with 75% loading) at the maximum distance from the cell D_{\max}

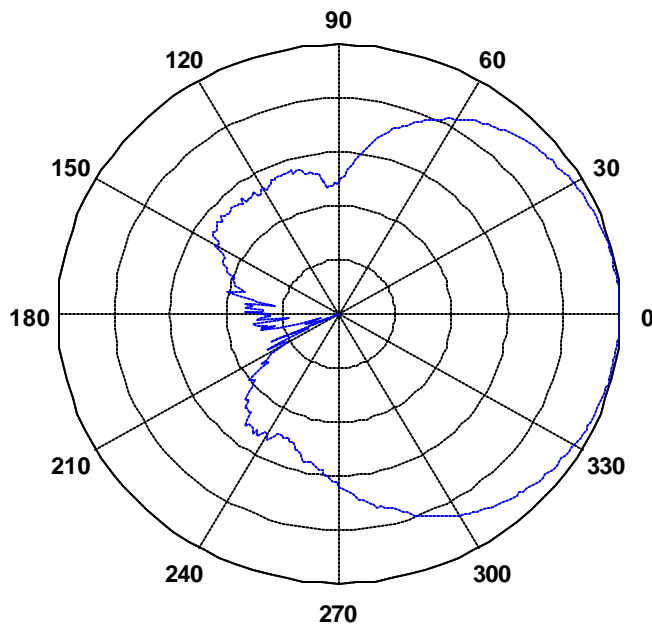
Differentiating the CDF given above results in a Uniform distribution of power in Watts, and an exponential distribution in dBm, shown below for the case of 33 dBm max power



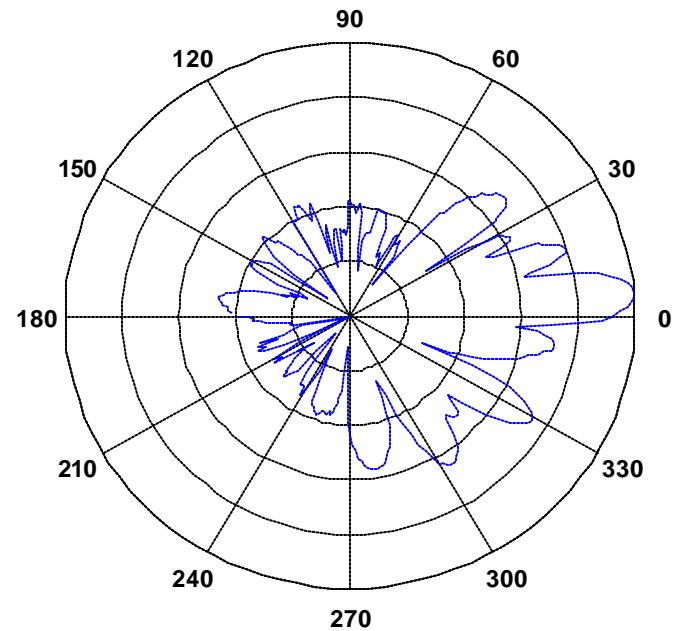
Base station antenna patterns

Patterns from commercially available antennas with 5 degree elevation “uptilt”

Azimuth cut



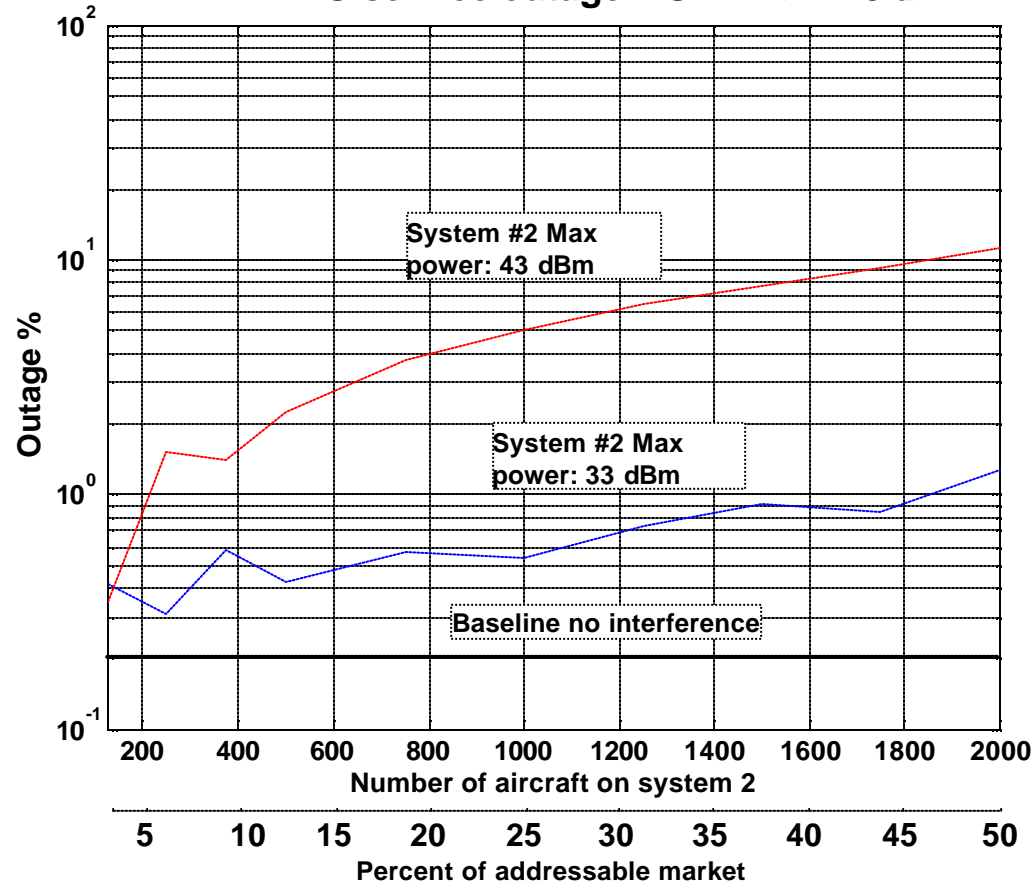
Elevation cut



Nationwide outage probability

Performance of system #1 with system #2 present

1xEvDO service outage if SINR < -12.5 dB



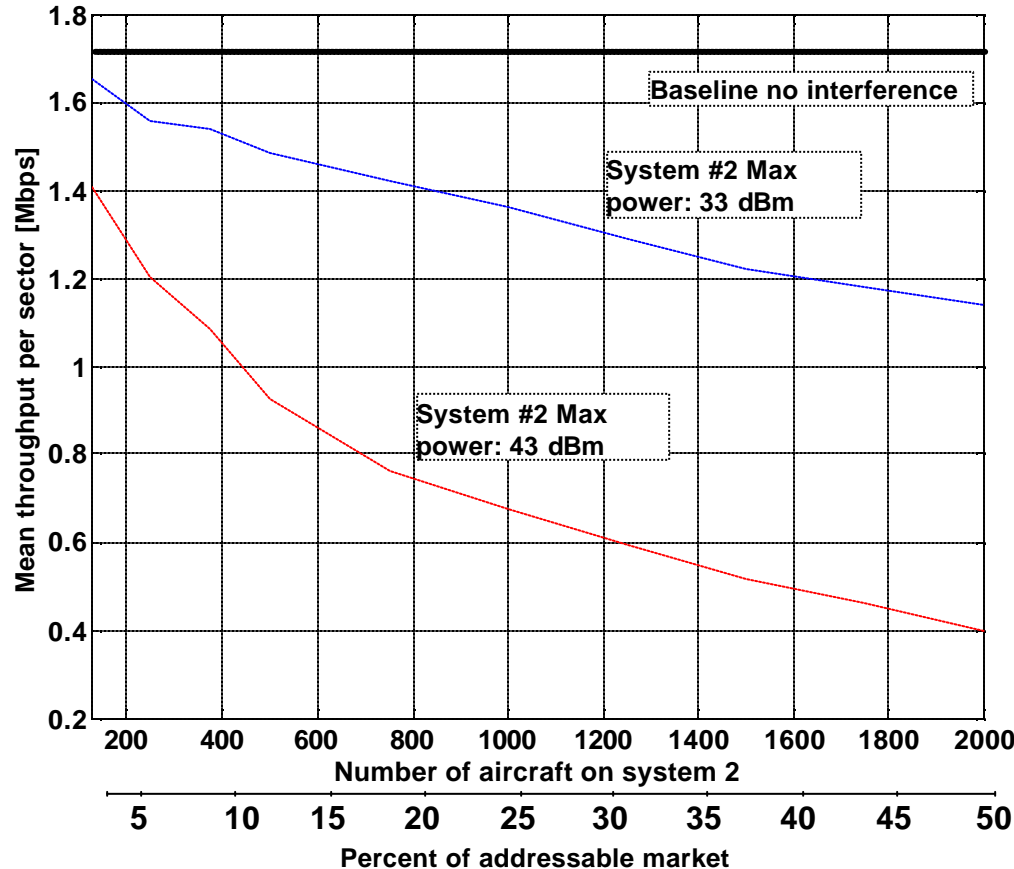
- 2000 interfering aircraft in the air at any time represents $\frac{1}{2}$ of the addressable market.
- This is equivalent to ~13 aircraft per BTS or ~4 aircraft per sector for a 3 sector system.
- 43 dBm maximum power from the aircraft seems to be a reasonable lower bound for a broadband service serving many passengers in each aircraft.
- The current narrowband system has a maximum aircraft transmit power of 43 dBm, a broadband service should transmit more power.

Max interferer power	Outage
No interferers	0.2 %
33 dBm	1.5 %
43 dBm	12 %

Two cases presented for different interferer maximum powers.

Throughput reduction

Performance of system #1 with system #2 present



- If system 2 increases number of aircraft beyond the 50% market share shown here, the throughput reduction for system 1 would be even greater.

Mean forward link throughput per sector with 2000 interferers present (50% market share)

Max interferer power	Outage
No interferers	1.7 Mbps
33 dBm	1.15 Mbps
43 dBm	400 kbps

Two cases presented for different interferer maximum powers.